

NGC 5084: A Massive Disk Galaxy Accreting its Satellites ?

Claude Carignan

Département de physique and Observatoire du Mont Mégantic, Université de Montréal

Stéphanie Côté

European Southern Observatory

Kenneth C. Freeman

Mount Stromlo and Siding Spring Observatories

Peter J. Quinn

European Southern Observatory

Received _____; accepted _____

To appear in the *Astronomical Journal*

ABSTRACT

The spectra of 34 galaxies within 20 arcmins (~ 100 kpc) of the lenticular galaxy NGC 5084 have been obtained using the FOCAP system on the Anglo–Australian 3.9m telescope. Nine objects are found with projected separations $\lesssim 80$ kpc and with radial velocities within ± 630 km s $^{-1}$ of the parent galaxy redshift. Using various techniques, their velocity differences and projected separations are used to estimate the mass of this S0 galaxy, which ranges from $6 \times 10^{12} M_{\odot}$ to $1 \times 10^{13} M_{\odot}$. With such a mass, NGC 5084 is one of the most massive disk galaxy known, with a $(M/L_B) \gtrsim 200 M_{\odot}/L_{\odot}$. In agreement with the models’ predictions of Quinn & Goodman (1986) but contrary to the results of Zaritsky *et al* (1993) obtained from their statistical sample, the properties of the satellites’ population show no evidence for the “Holmberg effect” and a clear excess of satellites in retrograde orbits. Several signs hint that this S0 galaxy has survived the accretion of several satellites.

1. Introduction

The nature and distribution of dark matter are still the most exciting questions of extragalactic astronomy. While for individual galaxies the mass-to-light ratio M/L_B ranges from 2 to $90 M_\odot/L_\odot$ (as derived from their rotation curves), this ratio shows a wide variety of sometimes contradictory values when it comes to binary galaxies and small groups. The most often cited values of M/L_B for these systems range roughly from 30 up to $600 M_\odot/L_\odot$ (Huchra and Geller 1982). However these values are uncertain since many estimates are suspected to be either polluted by interlopers wrongly assigned to the group, or to suffer from too stringent selection criteria.

A special type of group of galaxies is the one in which a central dominating massive galaxy is orbited by several dwarf satellite galaxies. On inspection of the SERC survey plate, NGC 5084 seems at first glance to be surrounded by at least two dozens satellites within 50 kpc (the adopted distance for NGC 5084 throughout this study is 15.5 Mpc, Zeilinger *et al* 1990). So by obtaining the redshifts of these objects it should be possible to find out the true companions and get rid of most interlopers. The relative radial velocities and projected separations of these satellites will then allow an estimate of the mass of NGC 5084, probing its potential further out than what is possible with an HI rotation curve.

Only a handful of studies have used this approach to calculate the mass of spirals. The difficulty resides in finding enough satellites to carry out such an analysis. The most populous system studied to date is the group of 5 dwarfs around NGC 1961 from Erickson *et al* (1987). They studied nine groups of satellites around spirals (between 1 to 5 satellites each), and concluded that only 4 primaries needed a massive dark halo to bind the satellites. Zaritsky *et al* (1993), hereafter ZSFW, conducted a large survey of satellites around Sb-Sc's and found 69 objects orbiting 45 primaries. Again their most populous system is NGC 1961

with its 5 dwarfs. But by analysing their whole sample as a statistical ensemble they derive a mass of the order of $\simeq 2 \times 10^{12} M_{\odot}$ within 200 kpc for a typical Sb-Sc galaxy similar to the Milky Way (Zaritsky & White 1994, hereafter ZW), in good agreement with recent estimates of the mass of the Milky Way (see for example Freeman, 1996).

This sample of satellites will not only be useful to estimate the mass of NGC 5084, but it should also be a good test for the theory of accretion of satellites by a parent disk galaxy elaborated by Quinn & Goodman (1986), hereafter QG, who made very definite predictions on the properties of the left-over satellites’ population after a Hubble time.

NGC 5084 is a lenticular galaxy with a very large rotational velocity ($\simeq 330 \text{ km s}^{-1}$) and an extended low surface-brightness disk, which is tilted at $\sim 5^{\circ}$ with respect to the brighter, inner stellar disk. The faint disk extends for at least 6.8 arcmin on both sides of the nucleus. In its inner one-third lies a dust lane which passes slightly to the south of the nucleus. Zeilinger *et al* (1990) showed that the change in position angle describing the tilt between the 2 structures (faint extended disk and bright inner one) is present in R as well as in B images, which hints that this misalignment is intrinsic and not due to dust absorption. The distorted nature of the inner regions suggests the possibility that this galaxy may be recovering from a recent merger event, probably with what was once a dwarf companion.

Neutral hydrogen was detected in large quantity in NGC 5084. The study by Gottesman and Hawarden (1986), hereafter GH, shows that the HI is distributed in a flat annulus, extending over most of the faint clumpy disk. The total HI mass yields a $M_H/L_B \sim 0.35$ which is very high for a galaxy of this type (van Driel & van Woerden 1991). Such a high (M_H/L_B) suggests again the possibility of a recent dwarf merger(s), with some gas being freshly accreted during the event. Without any further analysis, it is also clear from the HI data that NGC 5084 is a massive galaxy since its derived maximum velocity of 328 km s^{-1} (GH) is nearly twice the maximum velocity derived for a typical S0

galaxy (van Woerden, van Driel & Schwarz 1983).

2. Observations

The first step was to identify possible satellites by close inspection of the UK Schmidt III–a J survey plate. Within 22 arcmin of the galaxy (which corresponds to ~ 100 kpc at the distance of NGC 5084), 49 candidate satellite galaxies were identified. The coordinates of these objects were obtained by using the Space Telescope Guide Star Catalog software and also by measurements on the survey plate J576 with the Mount Stromlo PDS microdensitometer. The positions of the galaxies were determined to an accuracy of better than 1.2 arcsec rms.

With so many spectra to be obtained within such a small region of the sky, these observations were very well-suited for the Fibre-Optic Coupled Aperture Plate system (FOCAP, Boyle *et al* 1989) on the Anglo–Australian Telescope (AAT), used in conjunction with the Royal Greenwich Observatory (RGO) Spectrograph and the Image Photon Counting System (IPCS, Boksenberg 1978). The observations were carried out on the perfectly clear night of 1990 April 30th.

From the total of 56 fibres available in the bundle, 34 were positionned on candidate satellites, the remaining 15 satellites identified on the plate being either vignettted by the TV mirror, either too close from a prime candidate, or inaccessible within the 40 arcmin field. So the remaining 22 fibres were plugged on sky positions. The spectra were obtained using the 600 lines/mm grating, with a spectral resolution of 2 \AA and a spectral coverage of 2000 \AA , in the range of ~ 3550 to 5550 \AA targetting the CaII H & K, H β , [OIII] and Mg b triplet lines. Exposures on the program objects of 2000s were alternated with 200s exposures of a Cu-Ar arc lamp for wavelength calibration, for a total of 28 900s on our

objects through the night.

3. Data Reduction

The data reduction was performed with the software package FIGARO. The technique used to obtain the redshifts of the 34 objects was to cross-correlate their spectra with the ones of 2 template stars, following the method of Tonry & Davis (1979). For a handful of objects, including G8, emission lines were identified in the spectra and velocities were obtained by fitting a gaussian to the lines.

Redshifts were succesfully obtained for 28 objects, amongst which 8 were found to have velocities within $\pm 630 \text{ km s}^{-1}$ of NGC 5084 ($V_{\odot} = 1721 \text{ km s}^{-1}$), and are thus thought to be satellites. These are listed in Table 1, with their respective projected separation R and relative velocity Δv from NGC 5084, with errors in velocity given by:

$$\sigma_v = \frac{N \times vbin}{8B(1 + R)} \quad (1)$$

where N is the number of channels used in the spectrum, $vbin$ is the velocity increment per bin, B is the highest wavenumber where the Fourier Transform of the cross-correlation function (CCF) has appreciable amplitude, and R is the ratio of the height of the correlation peak to the height of an average noise peak in the CCF (Tonry & Davis 1979).

ESO576-G40 (G7 in the Table 1) is added to our sample of satellites: although not detected in our FOCAP run as it was inadvertently plugged in a not-known-to-be-dead fibre, it was previously detected in HI by GH, at $V_{\odot} = 2089 \text{ km s}^{-1}$. It will be assumed that all these objects are bound satellites of NGC 5084. This is a very reasonable assumption considering that they all have projected separations of less than $\simeq 80 \text{ kpc}$ of NGC 5084 which, in comparison, has a maximum optical diameter of 74 kpc ; and they all have radial

velocities within $\pm 630 \text{ km s}^{-1}$, which is less than twice the maximum rotational velocity of NGC 5084 ($V_{max} = 328 \text{ km s}^{-1}$). This projected separation cutoff was simply dictated by the field-of-view available with FOCAP. As for the relative velocity cutoff, it was determined from the observation that the next nearest Δv is 1240 km s^{-1} , ie: about twice the value of the last one retained (G4 with $\Delta v = 629 \text{ km s}^{-1}$). It therefore seems to indicate that NGC 5084 and its satellites' system have decoupled from the general Hubble flow and can be safely considered a self-gravitating ensemble.

The satellites are identified in Figure 1 and the radial velocity differences between the satellites and NGC 5084 are shown in Figure 2 as a function of their projected separation. Figure 3, which gives the Δv 's of all the candidates (satellites and background galaxies), shows clearly that this satellites' system is well isolated. While the retained satellites all have $\Delta v < 630 \text{ km s}^{-1}$, most of the other observed galaxies have $\Delta v > 10000 \text{ km s}^{-1}$ with only 3 objects with $1200 < \Delta v < 5300 \text{ km s}^{-1}$.

4. Mass estimate of NGC 5084

The radial velocities derived in the last section will now be used to estimate the mass of NGC 5084. From its maximum velocity of $V_{max} = 328 \text{ km s}^{-1}$ and the outermost measured radius of 7.5 arcmin (34 kpc), a Keplerian mass estimate (rV^2/G) of $M = 8.5 \times 10^{11} M_{\odot}$ is derived, leading to an exceptionnally large mass-to-light ratio of $M/L_B = 65 M_{\odot}/L_{\odot}$. NGC 5084 is clearly one of these supermassive disk galaxies, as referred to by Saglia and Sancisi (1988). Several galaxies that they list have even higher V_{max} , but NGC 5084 is the first one for which dwarf satellites are going to be used to probe the potential further out.

Let us first apply the virial theorem to estimate the mass of NGC 5084, which is the standard method for obtaining the mass of a self-gravitating system. We will be using 8 of

the 9 objects listed in Table 1, discarding G8 which appears to be a satellite of a satellite! It is closely orbiting G7 and so its kinematics surely reflects more its interaction with G7 than with NGC 5084. In the special case of a spherically symmetric collection of N test particles orbiting a point mass M , the virial theorem takes the form of (see Bahcall and Tremaine 1981, hereafter BT, for the derivation):

$$M_{VT} = \frac{3\pi}{2G} \left(\sum_{i=1}^N \Delta v_i^2 \right) / \left(\sum_{i=1}^N 1/R_i \right) \quad (2)$$

Using the values of Δv_i and R_i (and their errors) of Table 1, the virial mass is:

$$M_{VT} = 6.3(\pm 3.4) \times 10^{12} M_{\odot}$$

However, BT argue that this virial estimator is biased and inefficient. They show that $\langle M_{VT} \rangle$ is not necessarily equal to M for finite N and that M_{VT} does not converge to M as $N \rightarrow \infty$. They also complain that it weights the contribution from nearby particles too heavily. They have therefore proposed alternative estimators based on the projected mass, $q = (\text{projected distance}) (\text{radial velocity}) / G$. These estimators take the following forms:

$$M_{BT} = \frac{f}{\pi G N} \sum_{i=1}^N \Delta v_i^2 R_i \quad (3)$$

where $f = 16$ in the case of isotropic orbits, and $f = 32$ for radial orbits. Since there is no information on the distribution of eccentricities for the satellites' orbits, it is recommended to use the following estimator:

$$M_0 = 1/2 (M_{iso} + M_{rad}) = \frac{24}{\pi G N} \sum_{i=1}^N \Delta v_i^2 R_i \quad (4)$$

where M_{iso} is M_{BT} for the isotropic case and M_{rad} for the radial case.

Applying the BT estimators to our sample, these yield:

$$M_{iso} = 6.7 (\pm 3.5) \times 10^{12} M_{\odot}$$

$$M_{rad} = 1.3 (\pm 0.7) \times 10^{13} M_{\odot}$$

$$M_0 = 1.0 (\pm 0.5) \times 10^{13} M_{\odot}$$

BT have also carried out a series of Monte Carlo simulations from which they concluded that the virial mass is too often an underestimate, and that their projected mass estimator is more accurate. This BT estimator and the virial one share however some limitations. First, these estimators assume random phases, ie: the orbital phases of the satellites are taken to be uniformly and independently distributed on $[0, 2\pi]$. This is a good approximation only if the satellites have completed many orbits. Indeed calculating the period of a test particle at 82.95 kpc (our maximum projected separation) with a velocity of 328 km s^{-1} ($=V_{max}$ of NGC 5084) gives about 1.5×10^9 years, allowing for several orbits within a Hubble time, and so this random-phases assumption is appropriate for our sample. Second the potential is assumed to be generated by a central point-mass, which is inadequate here as the satellites are at very small projected separation and are probably orbiting within the dark halo of NGC 5084. ZW circumvent this limitation by applying to their statistical sample of satellites a more sophisticated method using scale-free models, originally developed for dynamical studies of binary galaxies (Turner 1976; White 1981). The underlying assumption of these models is that small-scale galaxy clustering exhibits no characteristic length-scale. The interaction potential and the density profile of satellites are taken to be power-laws. As will be discussed further, N-body simulations of accretion of satellites by a parent disk galaxy make definite predictions on the properties of the left-over satellites' population after a Hubble time. They find very short decay times for prograde orbits satellites (QG). This is especially valid for satellites at distances within a disk-diameter

from their primary as is roughly the case here. So under these conditions one must perhaps question the appropriateness of the scale-free assumption. In any case ZW found good agreement between the BT mass estimates and the scale-free models estimates. Therefore our best estimate for the mass of NGC 5084 is $\sim 1.0 \times 10^{13} M_{\odot}$, with an uncertainty of a factor of 2. *This is the highest mass yet ever derived for a disk galaxy.*

We have recalculated these estimates considering the possibility that the 2 most extreme objects (in terms of $\Delta v^2 R$), G4 and G7, are not bound to the system. We see from Figure 2 that these two galaxies lie well above general trend defined by the rest of the sample, so it is worth considering the consequences of their exclusion. The remaining 6 satellites then give:

$$M_{VT} = 3.9 \times 10^{12} M_{\odot}$$

$$M_0 = (5.2 \pm 2.9) \times 10^{12} M_{\odot}$$

which is still *the highest known mass for a disk galaxy.*

Taking for NGC 5084 the luminosity derived by Zeilinger *et al* (1990) of $L_B = 1.6 \times 10^{10} L_{\odot}$, a very large mass-to-light ratio of $(M/L_B) = 215 M_{\odot}/L_{\odot}$ is derived. This indicates a tremendous amount of dark matter associated with this galaxy. The increase of more than a factor of 3 of the (M/L_B) over the value derived by GH is not surprising since this study is probing the mass distribution and the dark halo component to much greater radii (~ 80 kpc) than the last measured point of the HI rotation curve (~ 34 kpc). The main uncertainty on this ratio is probably coming from the correction for extinction due to dust within the galaxy which could have been underestimated. For example, if the total magnitude was 0.5 mag. brighter, this would reduced the (M/L_B) to 135. However, the IRAS fluxes measured for NGC 5084 (Knapp *et al.* 1989) suggest a normal dust content for its morphological type.

5. Discussion

As mentioned earlier, Saglia and Sancisi (1988) have compiled a list of the most supermassive disk galaxies known. However these masses are only indicative masses ($M = R_{25} \times V_{max}^2/G$) and it is more than probable that if a similar analysis as the one done here for NGC 5084 could be carried out, a few of these would probably be even more massive than NGC 5084.

It is interesting to note that several of these supermassive galaxies are reported to be clearly asymmetric in their light and/or in their HI distribution. As we have seen, NGC 5084 is a disk galaxy with an intrinsically distorted structure, and therefore its anomalies make it typical of its supermassive class. This has led Saglia and Sancisi (1988) to propose that supermassive spirals might be forming a distinct category of galaxies with definite properties instead of being viewed as the extreme tail of the mass distribution. These galaxies have most probably accreted some of their satellites, which have during the process disturbed the stellar disk. Recently, Huang & Carlberg (1995) have indeed shown with self-consistent disk+halo+satellite N-body simulations that the disks of the primaries get mainly tilted (rather than thickened) by infalling satellites. This is because large satellite orbital angular momenta which are not aligned with disk rotational angular momenta can easily tilt the disks, and tidal stripping of satellites in the dark halos can greatly weaken the satellite’s impact on the disks. A 5° tilt as is observed in NGC 5084 would correspond to the infall of a satellite as massive as roughly 16% of the disk-mass of NGC 5084, according to their simulations.

Let us now compare our results with the model’s predictions of QG, and with the results of ZSFW using their statistical sample. First, the “Holmberg effect”. Holmberg (1969), studying a sample of 218 apparent companions at less than $R \leq 50$ kpc of 58 parent spiral galaxies, claimed that satellites seem to avoid a zone of $\pm 30^\circ$ from the plane of the

primary which could suggest that they are the systems which are preferentially accreted. ZSFW also said that their sample shows some evidence for the “Holmberg effect”. Looking at Table 1 and Figure 4, there is surely no evidence of this effect in this restricted sample with half of the satellites within the $\pm 30^\circ$ zone. This effect was not seen either in the simulations of QG. There is no clear indication either in our sample of any trends in the satellites properties as their projected separation increases, namely if their sizes increase, or if they become of lower surface-brightness, or if they tend to be of later Hubble types (dIrrs), all of these three trends being mildly present in the ZSFW sample.

Finally, another prediction of the QG’s theory of satellites accretion is that there should be a net excess of satellites in retrograde orbits since the parent galaxy should have accreted most of the satellites in direct orbits within a Hubble time. They found in their N-body simulations that the decay times are a factor of 10 times larger for bodies in retrograde orbits than for those in direct orbits. Thus, the majority of satellites on prograde orbits should have already been accreted within a Hubble time, while most of the ones in retrograde orbits should still be at reasonable distances from the primary galaxy. The final column of Table 1 compares the *sign* of Δv for the satellite, and the sign of the rotational velocity of the HI in NGC 5084 on the same side of the minor axis as the satellite. (P) denotes that the satellite velocity and the HI velocity have the same sign, while (R) denotes that the signs are opposite. We cannot infer from an (R) or a (P) whether an individual satellite orbit is retrograde or prograde. However it is clear that 7 of our 8 satellites have an (R) in Table 1, which does suggest a predominance of retrograde orbits. This is in contrast to the results of ZSFW who found nearly equal numbers of (R) and (P) orbits.

6. Summary and Conclusions

From the spectra of 34 objects identified to be lying close to NGC 5084, 8 galaxies are found with redshifts within $\pm 630 \text{ km s}^{-1}$ of this system, and projected separations ≤ 80 kpc of it. They are used to probe the potential of NGC 5084. Using the projected mass estimator, a mass of $M \simeq 1.0 \times 10^{13} M_{\odot}$ is calculated, therefore making of NGC 5084 the most supermassive disk galaxy known so far. Such a huge mass strongly suggests the existence of a considerable quantity of dark matter associated with NGC 5084. Zeilinger *et al* (1990) already proposed that NGC 5084’s massive structure might have been built by sequential accretions of mass from its environment. With so many close dwarf companions this possibility cannot be excluded.

An analysis of the properties of the satellites’ sample shows no sign of the “Holmberg effect” and a clear preference for retrograde orbits. This agrees with QG’s N-body simulations who find that parent galaxies do not accrete preferably satellites with $\Theta \leq \pm 30 \text{ deg}$ from the plane of their disks, but accrete more efficiently those with direct (prograde) orbits. The fact that most of the prograde orbits satellites have disappeared, that NGC 5084 is unusually HI-rich, and that its outer disk is tilted (which is the signature of small-mass satellites accretion according to Huang & Carlberg 1995 N-body simulations), all hint strongly that this S0 has survived successfully the accretion of many low-mass objects.

We are grateful to Stephen Gottesman for his referee’s report, which improved the content of this paper. We would like to thank Sylvie Beaulieu and the Space Telescope’s Guide Star Catalog group for providing the software and the assistance in determining the objects’ accurate positions. S.C. acknowledges the support of an A.N.U. scholarship as well as a F.C.A.R. scholarship, and C.C. a grant from NSERC.

REFERENCES

- Bahcall, J.N., & Tremaine, S. 1981, ApJ, 244, 805 (BT)
- Boksenberg, A. 1978, Report: Performance of the UCL IPCS
- Boyle, B., Gray, P., & Sharples, R. 1989, AAO FOCAP System
- Erickson, L.K., Gottesman, S.T., & Hunter Jr., J.H. 1987, Nature, 325, 779
- Freeman, K.C. 1996, in *Unsolved Problems of the Milky Way*, ed. L. Blitz & P. Teuben (Dordrecht: Kluwer), p. 645
- Gottesman, S.T., & Hawarden, T.G. 1986, MNRAS, 219, 759 (GH)
- Holmberg, E. 1969, Arkiv Astr., 5, 305
- Huang, S., & Carlberg, R.G. 1995, Preprint astro-ph/9511076, submitted to ApJ
- Huchra, J., Geller, M., 1982, ApJ, 257, 423
- Knapp, G.R., Guhathakurta, P., Kim, D.-W. and Jura, M. 1989, ApJS, 70, 329
- Quinn, P.J. & Goodman, J. 1986, ApJ, 309, 472 (QG)
- Saglia, R.P., & Sancisi, R. 1988, A&A, 203, 28
- Tonry, J.R., & Davis, M. 1979, AJ, 84, 1511
- Turner, E.L. 1976, ApJ, 208, 304
- van Driel, W., & van Woerden, H., 1991, A&A, 243, 71
- van Woerden, H., van Driel, W. & Schwarz, U.H. 1983, in *IAU Symposium 100, Internal Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), p. 99
- White, S.D.M. 1981, MNRAS, 195, 1037
- Zaritsky, D., Smith, R., Frenk, C. & White, S.D.M. 1993, ApJ, 405, 464 (ZSFW)

Zaritsky, D., & White, S.D.M. 1994, ApJ, 435, 599 (ZW)

Zeilinger, W.W., Galetta, G., & Madsen, C. 1990, MNRAS, 246, 324

Table 1. Orientation parameters of the satellites.

Object	R.A. Dec (1950.0)	Projected separation (kpc)	Relative radial velocity (km s ⁻¹)	Angle from the plane (°)	Prograde or Retrograde orbits
G1	13 16 40.1 -21 20 27	82.95	−34 (±96)	60	R
G2	13 16 47.4 -21 31 42	50.15	−232 (±136)	25	R
G3	13 17 04.4 -21 38 16	37.48	−260 (±57)	22	R
G4	13 17 29.7 -21 44 26	48.00	−629 (±123)	71	R
G5	13 17 54.5 -21 37 03	25.70	+485 (±118)	46	R
G6	13 17 59.7 -21 30 21	30.94	−381 (±125)	16	P
G7	13 18 00.9 -21 47 21	66.98	+368 (±3)	79	R
G8*	13 18 06.7 -21 47 35	70.65	+359 (±6)	—	—
G9	13 18 20.4 -21 29 24	52.29	+173 (±90)	9	R

*taken out of the sample

Fig. 1.— Optical identifications for the satellites of Table 1.

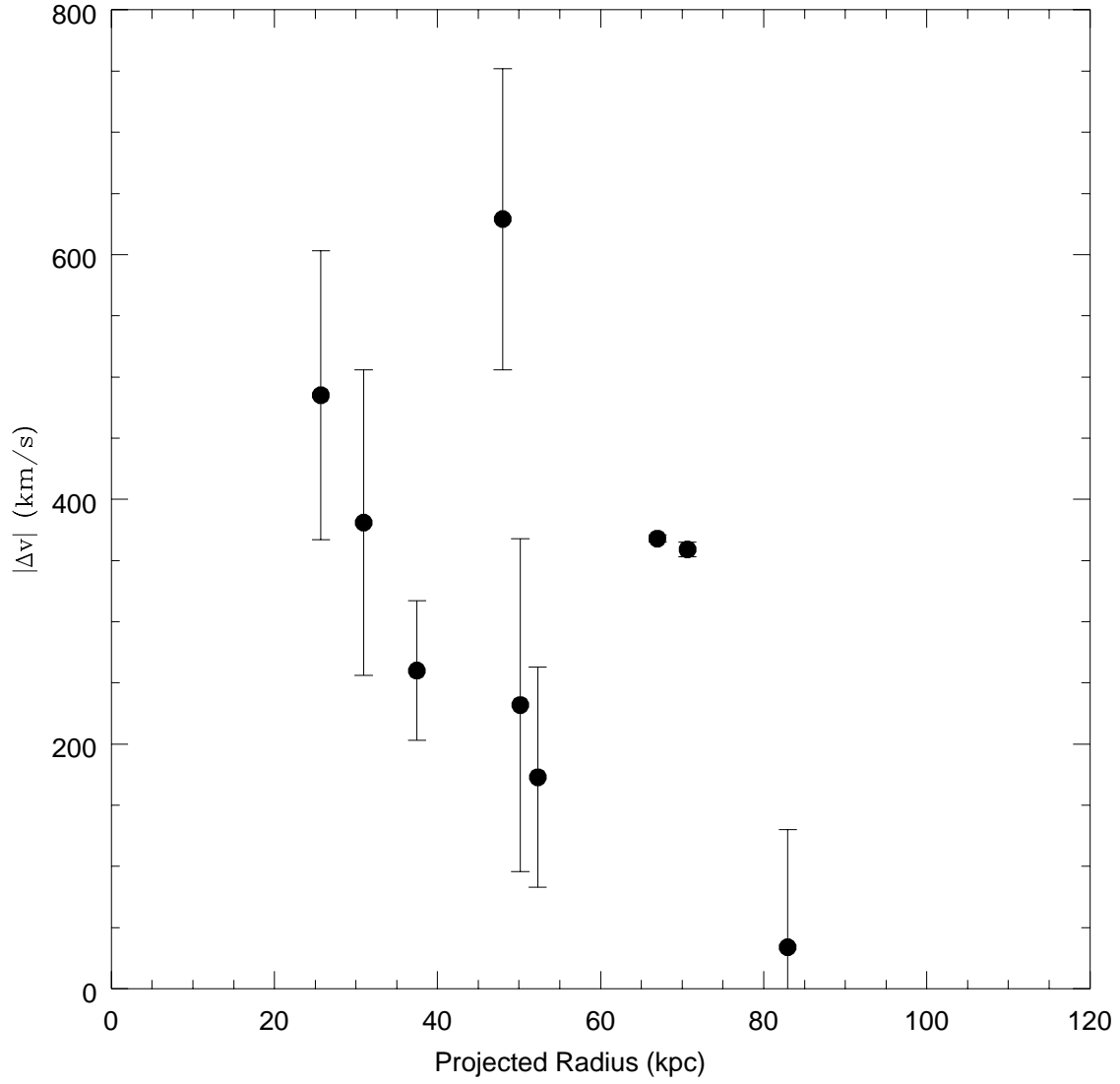


Fig. 2.— The absolute value, $|\Delta v|$, of the radial velocity difference between a satellite and NGC 5084, as a function of its projected separation on the sky.

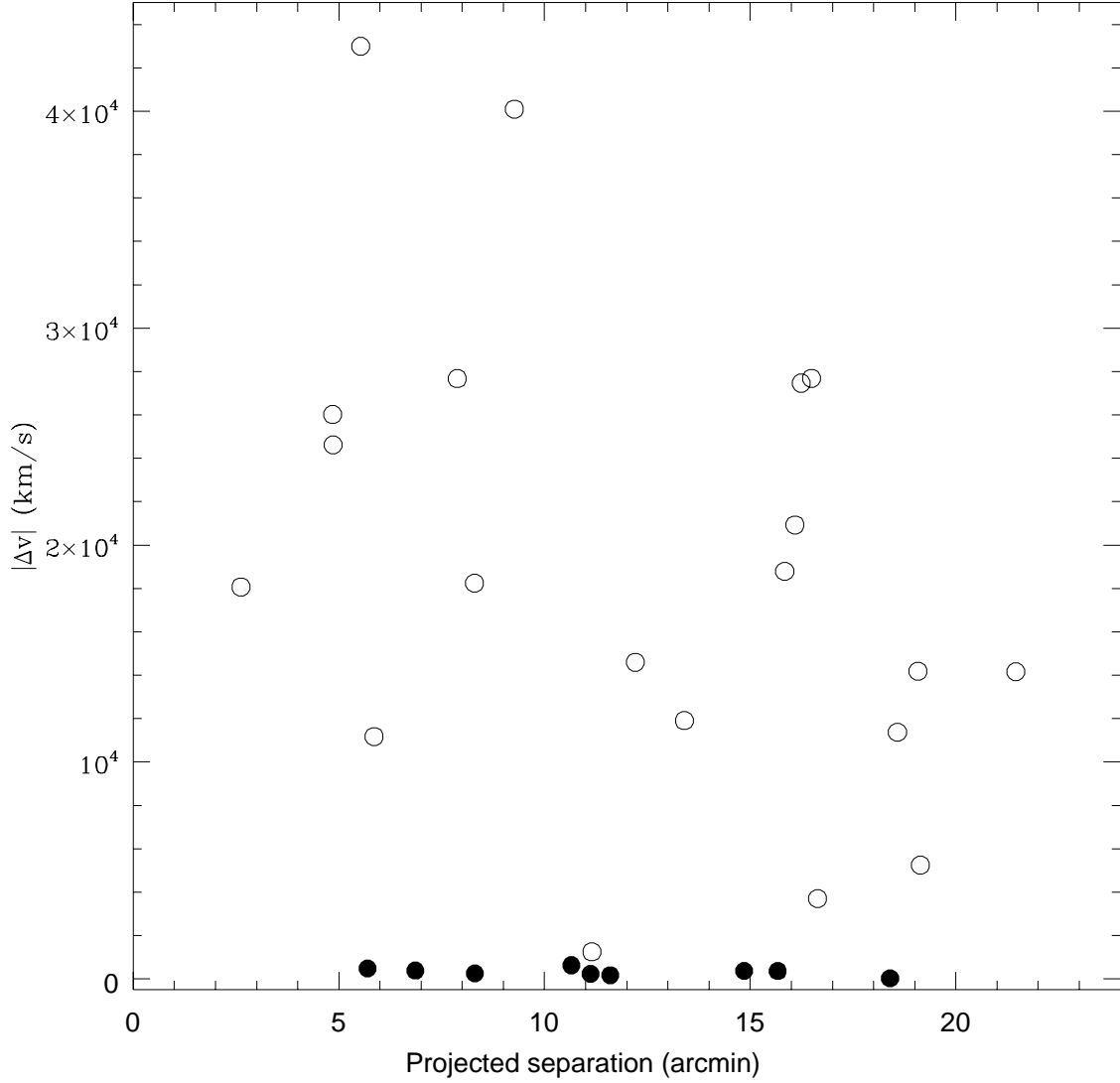


Fig. 3.— Δv vs projected separation in arcmin for the 28 detected objects and for G7 which had a previously known redshift. The filled circles are the objects identified as satellites while the open circles are the background galaxies. The satellites have Δv 's $< 630 \text{ km s}^{-1}$ while most background galaxies have $\Delta v > 10\,000 \text{ km s}^{-1}$ with only 3 galaxies with redshift between 1200 and 5300 km s^{-1} .

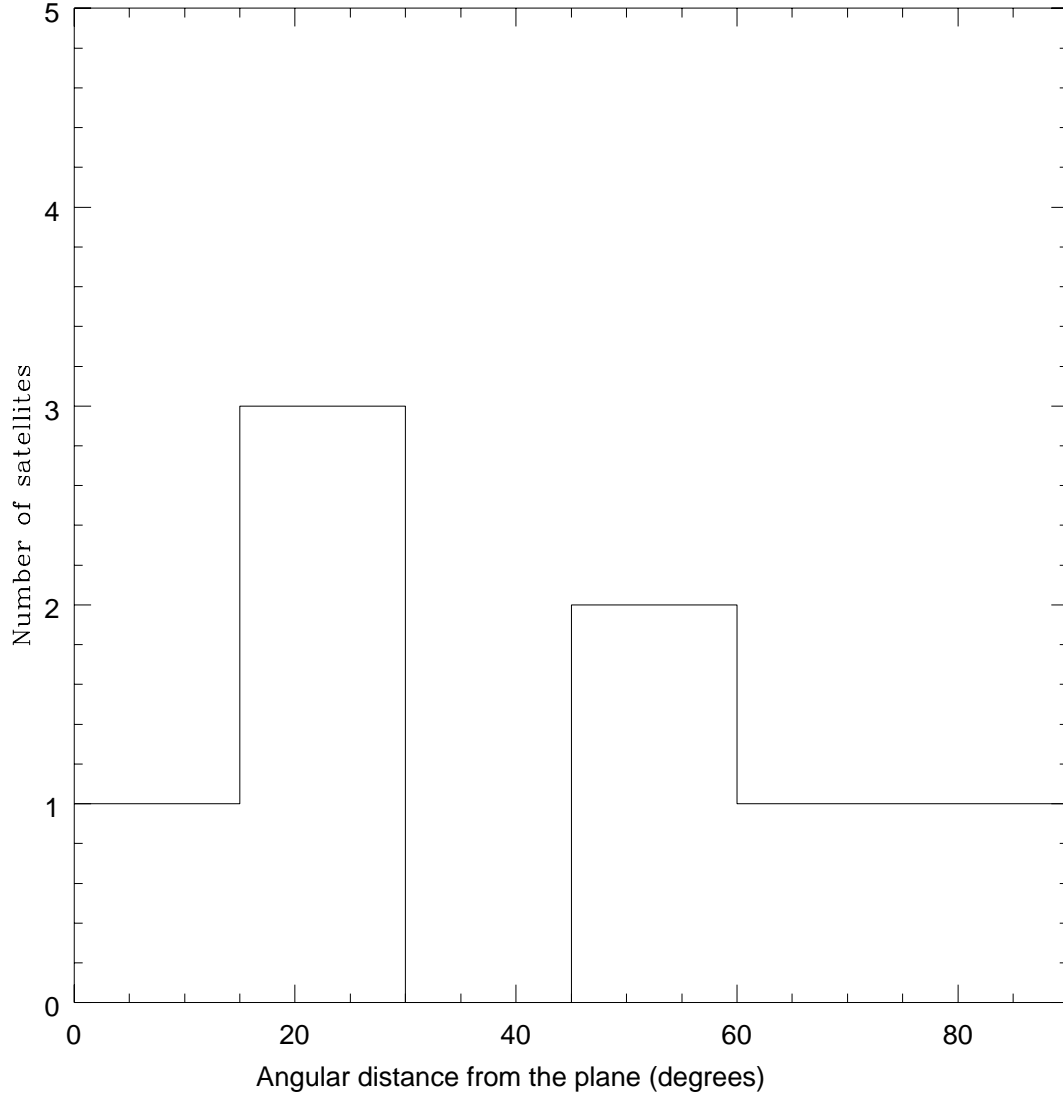


Fig. 4.— Histogram of the number of satellites as a function of the angular distance from the plane. It can be seen that half of the satellites are in the $\pm 30^\circ$ zone of avoidance predicted by the “Holmberg effect”.

This figure "pfig1.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/9704032v1>